Subject:

Response to reviewer #1 for manuscript [egusphere-2025-3594: "Thermodynamic and dynamic drivers underlying extreme central Arctic sea ice loss"]

Text in black: Reviewer's comments; Text in blue: Authors' responses.

Introduction

This manuscript explores the changes to central Arctic sea ice concentration (SIC) by identifying episodes of intense SIC loss ELSEs or Extreme Loss Sea ice Events. This is done through a rare event threshold and is inferred from the NSIDC SIC record. Secondly, the manuscript performs Empirical Orthogonal Function analysis upon the SIC fields to identify two dominant modes of SIC anomaly. Finally, the authors budget the two modes of SIC using PIOMAS and explore the connections to atmospheric feedbacks. The paper is well written, thorough and the visual representations are well produced. However, there are some considerations to make before progressing with this manuscript, specifically with the clarity of methodology.

Novelty

The novelty in this paper is rooted in the identification of modes of SIC ELSEs. Namely, the East-West seesaw (EWSM) and Pacific-Atlantic seesaw (PASM) modes. These are interesting concepts for explaining the differing behaviours of the Arctic sea ice system during loss events. As well as the interpretation of atmospheric feedbacks that induce these modes.

We greatly appreciate your detailed review of this manuscript, which has significantly helped us improve the manuscript.

Positioning

The paper is well placed within the literature to move forward with identifying system changes to the central Arctic sea ice regime. However, there are several key papers within the field that are not cited. See references.

We thank you for the valuable references, which we will adopt and cite to enhance our paper.

The sea ice budget diagnostic method used in this study is closely related to Holland and Kwok (2012) and Holland and Kimura (2016). Their works have well quantified the contributions to sea ice variations in both the Arctic and Antarctic, laying the foundation for the sea ice budget diagnostic analysis. Massonnet et al. (2018) demonstrates that sea ice variations mainly depend on the mean state (primarily SIT) of sea ice, which emphasizes the crucial role of SIT in the sea ice budget analysis here. These references highlight the necessity of improving the elaboration of our methods. For specific details, refer to the italicized part of our response to the second question below. In addition, Massonnet et al. (2018) argues that Arctic sea-ice change is tied to its mean state mainly through thermodynamic processes. This supports the conclusion of this study that the first two modes of sea-ice changes in the central Arctic are mainly influenced by thermodynamic effects and we will present this connection in the revised manuscript.

General Comments

The authors should confirm the prevalence and trend of SIC ELSEs using an alternative SIC product, e.g. OSISAF-401. I imagine this to have minimal change in event distribution; however, the impact upon EOF modes may be stronger. The work is robust in using multiple reanalysis datasets for atmospheric variables; the same approach should be taken concerning the SIC product.

We appreciate your constructive comments. Validating the robustness of SIC ELSEs and EOF modes is crucial to the research significance of this paper.

We note that the OSISAF-401 dataset, with a time span from 2005 to the present, does not cover the research period of this study and is thus inappropriate for use. The OSISAF-450a1 product spans 1978–2020, while OSISAF-430a serves as its supplementary dataset covering 2021–2025. The two products are suitable for this study, and numerous studies have used them for research about the Arctic (Belter et al., 2021; Docquier and Koenigk, 2021; Sumata et al., 2022, 2023; Tian et al., 2022). Therefore, we adopt OSISAF-450a1 and OSISAF-430a for validation in this study.

The spatial pattern of the central Arctic derived from OSISAF data is nearly identical to that from NSIDC, though the extent of the central Arctic in OSISAF data is slightly larger (Fig. R1a, b). The seasonal and interannual variability characteristics of sea ice in OSISAF data are consistent with those in NSIDC, but with smaller amplitudes (Fig. R1c, d). While the distribution of ELSEs between the two datasets differs in winters after 2015, both datasets effectively capture the key features of ELSEs (Fig. R1e): 1. The amplitude of ELSEs is stronger in summer than in winter; 2. 1990, 2007, 2012, 2016, and 2020 are typical years with ELSEs; 3. The frequency and intensity of ELSEs have increased significantly in recent years. In summary, the comparison between OSISAF and NSIDC SIC datasets indicates that the distribution and characteristics of ELSEs are robust.

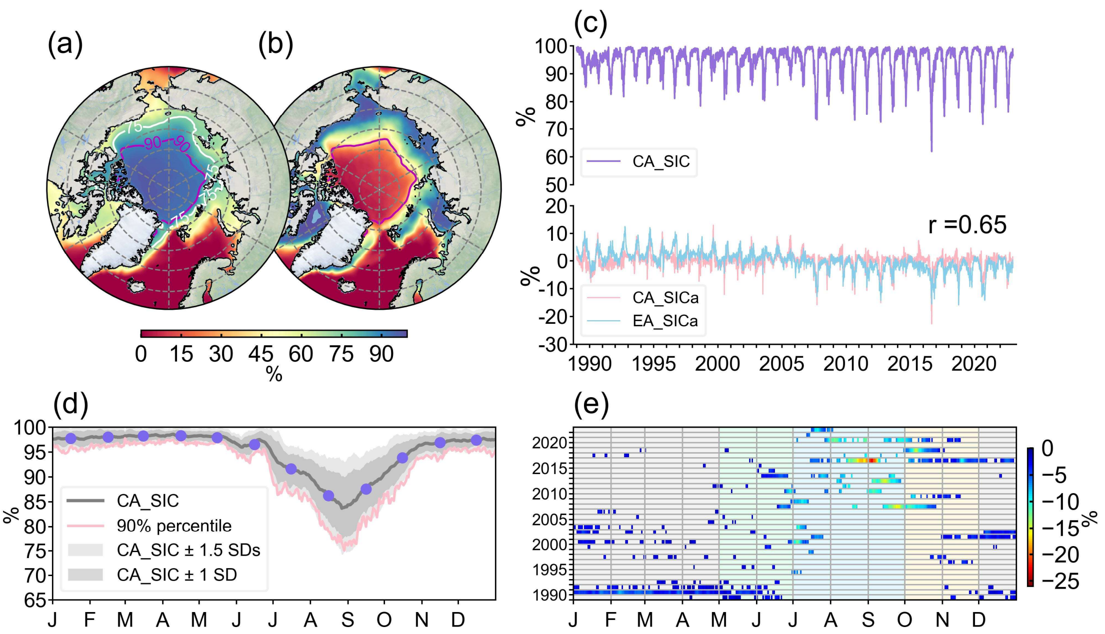

Figure R1. The same as Fig. 1 in the manuscript but for OSISAF SIC product results.

When comparing the standardized SIC anomaly fields of ELSEs, the most notable feature is that the signal in winter 1990 from OSISAF data is significantly stronger than that from NSIDC, while the signal in November and December 2016 is relatively weaker (Fig. R2a). The spatiotemporal modes derived from EOF decomposition using OSISAF are nearly identical to those from NSIDC, with the caveat that the order of the first two modes is reversed (Fig. R2b, c). The PASM is prominent in 1990; thus, the stronger signal in 1990 from OSISAF data compared to NSIDC (Fig. R2a) increases the variance contribution of PASM, making it the first EOF mode. Above all, despite slight differences in the central Arctic region, ELSEs distribution, and standardized SIC anomaly fields of ELSEs between the two datasets, both ultimately identify the EWSM and PASM, confirming the robustness of these two modes in the sea ice variability over the central Arctic.

Relevant contents and figures will be added to the revised version and supplementary information.

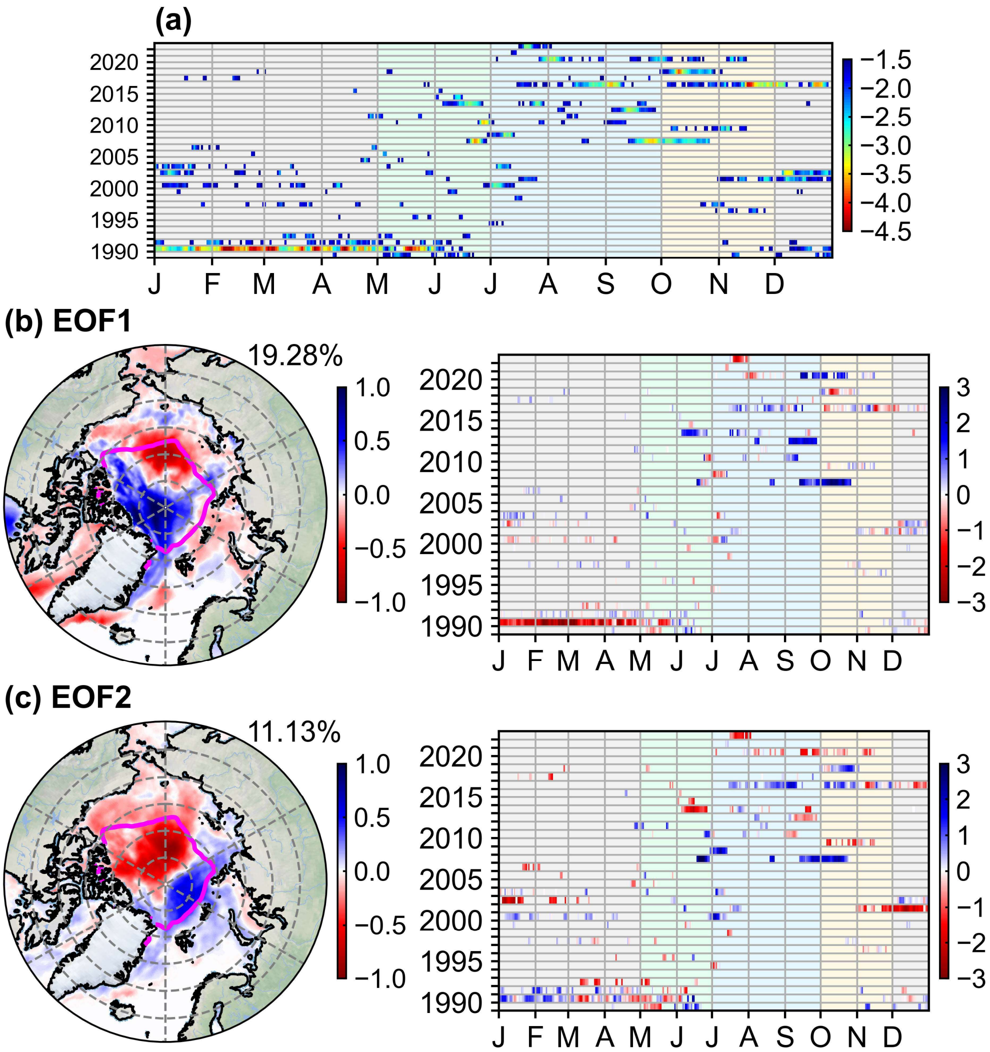

Figure R2. The same as Fig. 2 in the manuscript but for OSISAF SIC product results.

It is not obvious to me where the SIC budget is drawn from. Are the drift products used within the budget all from PIOMAS, or are they observational? If the budget is solely constructed from PIOMAS, how well does PIOMAS align with the observations, not only on the existence of ELSEs but also the distributions? If PIOMAS does not produce any ELSEs, how can the sea ice budget be well constrained or relevant for these modes? The whole methodological section on budgeting needs to make clear what is used and why.

Thanks for your reminder regarding the lack of necessary elaboration in the Methods section of the paper.

In the sea ice budget diagnosis, we used observed data of SIC and SIM (Sea Ice Motion) from NSIDC, which ensures the robustness of ELSEs in the diagnostic process. Since satellites cannot directly observe SIT (Sea Ice Thickness), NSIDC lacks SIT data with the spatiotemporal coverage and resolution required for this study. Therefore, we adopted SIT data from PIOMAS. It is worth noting that the diagnostic analysis combining observational and reanalysis data introduces an equation closure issue. We again appreciate the references you provided; through these references and those citing them, we found that previous studies have analyzed and discussed the equation closure issue caused by different data sources, concluding that it is reliable to use NSIDC SIC and PIOMAS SIT data for sea ice budget diagnosis.

We will revise the manuscript based on the *following text* to enhance the clarity of the Methods section.

Previous studies proposed using SIC budget to diagnose sea ice changes, in which the advection term, divergence term, and residual term (including thermodynamic processes and mechanical processes related to ridging and rafting) constitute the total SIC budget (Holland and Kimura, 2016; Holland and Kwok, 2012). Schroeter et al. (2018) replaced the SIC budget with the sea ice volume budget, thereby enabling SIT changes to include mechanical processes like ridging and rafting and making the residual term directly represent thermodynamic processes; this method has been widely used (Bi et al., 2023; Ding et al., 2025; Lukovich et al., 2021).

The sea ice volume budget analysis requires SIC, SIM, and SIT data, among which SIC and SIM are derived from NSIDC observational data in this work to ensure the robustness of ELSEs in the diagnostic process. Previous studies have indicated that the simulation bias of SIT dominates the accuracy of Arctic sea ice simulation and prediction (Massonnet et al., 2018). Therefore, SIT data is crucial for the diagnostic analysis of sea ice budget. Given that SIT cannot be directly observed by satellites, we use the SIT reanalysis data from PIOMAS here.

It should be noted that the combination of observational and reanalysis data for budget diagnosis involves the equation closure issue. Previous studies proposed the Lagrange multiplier algorithm to address the issue (Mayer et al., 2018). Existing research has used this method to conduct sea ice budget analysis based on NSIDC and PIOMAS data (Ding et al., 2025; Lukovich et al., 2021). They found that the difference between the original budget terms and those corrected by the Lagrange multiplier algorithm is negligible, indicating the sea ice budget diagnostic method combining NSIDC and PIOMAS data here is reliable.

There is a clear change in the behaviour of ELSEs of the PASM in Figure 2c. Naturally, there should be a discussion about the shifting seasonality of this phenomenon that the work is missing.

Thank you for your academically insightful comment; this is a very interesting phenomenon.

As shown in Fig. 2c, the PASM mainly exhibits negative phases in winter and positive phases in spring and summer. The most typical negative phase events occurred in 1990, 2002, and 2016; the most typical positive phase events occurred in 2007, 2012, and 2016. To our knowledge, the surface layer of the Arctic Atlantic sector was dominated by a strong low-pressure system in the winter and spring of 1990, while a significant low-pressure system was present in the Pacific sector during the summer of 2012. These low-pressure systems are conducive to the occurrence and maintenance of Arctic cyclones. Considering that the thermodynamic and dynamic coupling effects of Arctic cyclones play an important role in forcing sea ice reduction (Aue et al., 2022; Cavallo et al., 2025; Finocchio et al., 2020, 2022; Lukovich et al., 2021), we hypothesize that Arctic cyclones are a key factor contributing to the seasonal phase transition of the PASM.

Based on the cyclone identification and tracking algorithms developed by Zhang et al. (2004) and Crawford and Serreze (2016), we created an Arctic cyclone dataset using ERA5 sea level pressure data.

We found that in the central Arctic, super cyclones during typical negative-phase PASM events only occur in the Atlantic sector (Fig. R3d–f), whereas during typical positive-phase PASM events, the Pacific sector is also affected by super cyclones (Fig. R3a–c). Furthermore, compared with the negative phase, the positive phase of PASM is characterized by a significant decrease in the probability density of super cyclones in the Atlantic sector and a significant increase in the Pacific sector (Fig. R3g); similarly, from winter to summer, the probability density of super cyclones decreases in the Atlantic sector and increases in the Pacific sector (Fig. R3h). Previous studies have conducted numerous case analyses on the impact of super cyclones on Arctic sea ice reduction (Lukovich et al., 2021; Stern et al., 2020; Tian et al., 2022). Our findings are consistent with these cases in terms of temporal distribution and the spatial pattern of sea ice reduction. These results fully indicate that the seasonal phase transition of PASM is closely linked to super cyclones.

We will add relevant content in the revised version to discuss this issue, thereby enriching the understanding of PASM.

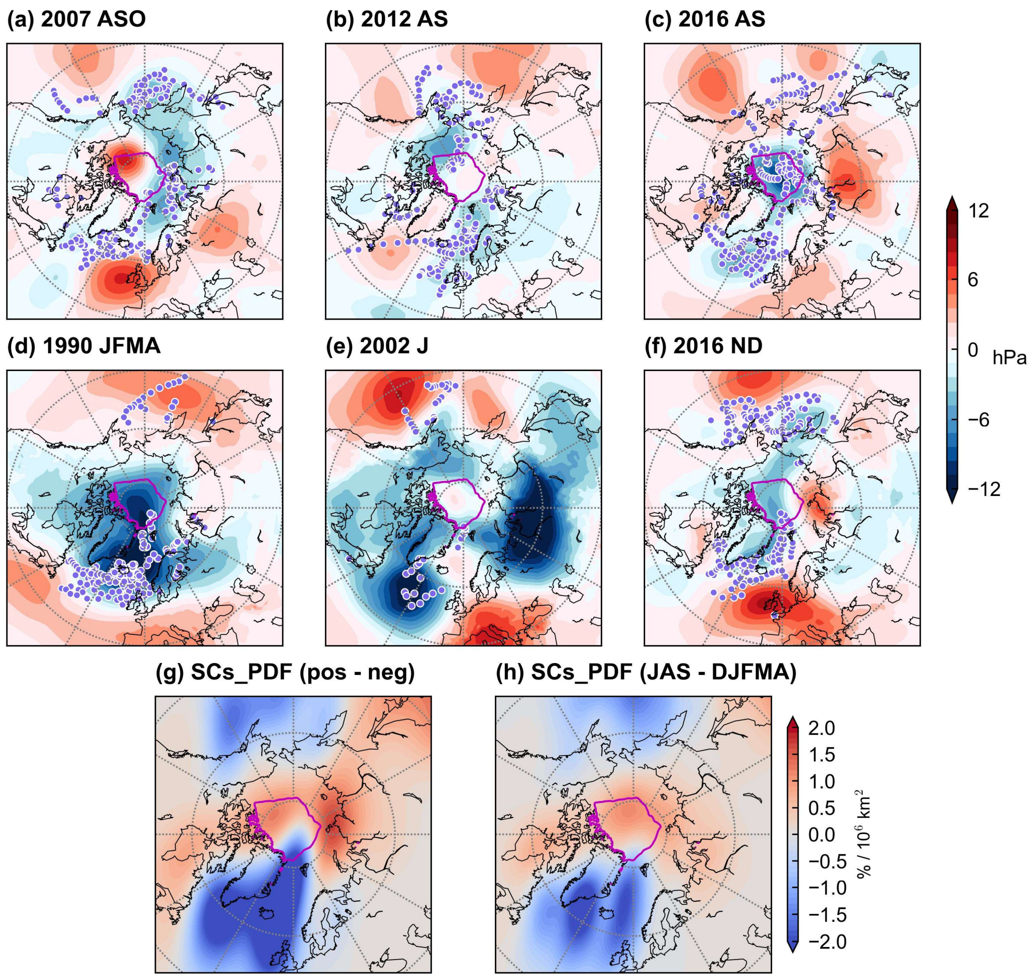

Figure R3. Sea level pressure anomalies (shadings) and distribution of super cyclones (central pressure >1.5 SDs below the climatological monthly mean; purple dots) during typical positive-phase (a-c) and negative-phase (d-f) PASM events. Differences in super cyclone probability density between typical positive and negative phases of PASM (g) and between winter and summer (h). Magenta lines represent the central Arctic.

The brief section on Arctic amplification in the introduction is well read but needs to be restructured for clarity.

We will revise "*Amidst the context of global warming, the Arctic experiences a greater warming rate that is approximately twice the global average, a phenomenon commonly referred to as Arctic Amplification (Pithan and Mauritsen, 2014; Serreze and Barry, 2011). Recent research has highlighted that Arctic Amplification has been underestimated (Chylek et al., 2022; Rantanen et al., 2022). Both observations and modeling studies have revealed that the Arctic region is warming at a rate approximately four times faster than the global average, with the potential to surpass eight times that of the global average in winter (Davy and Griewank, 2023).*" to "*Amidst the background of global warming, the Arctic is warming at a rate roughly twice the global average—a phenomenon widely known as Arctic Amplification (Pithan and Mauritsen, 2014; Serreze and Barry, 2011). However, recent studies have indicated that this amplification has been underestimated: both observational and modeling studies now reveal that the Arctic is warming at a rate about four times (even potentially exceeding eight times during winter) faster than the global average (Chylek et al., 2022; Davy and Griewank, 2023; Rantanen et al., 2022).*"

We have improved the logical coherence of this paragraph by incorporating dashes, colons, the conjunction "however", and temporal markers such as "now". We aim to present the evolving understanding of the Arctic Amplification phenomenon concisely and clearly through such expressions. We would greatly appreciate any further suggestions if possible.

Technical Comments:

L27-28: Remove "a greater" in the sentence on Arctic Amplification

L35: "Significant declining trend" not a "significant decline trend"

L38-39: "acts as a pivotal modulator to drive the evolution" should be "acts as a pivotal modulator *of* the evolution"

L43: "What's more" is too informal

L119: "Cases when the principal components" should be "Cases in which …"

L290: remove "directly"

L440: "Whatever" should be However or Nevertheless

We sincerely appreciate your thorough revisions, which have significantly improved the manuscript's language. We will incorporate all suggestions in the revised version.

Figures/Tables:

Figure 11 – either the stippling needs to change to a more appropriate and eye-catching colour, or the colourmaps. The cyan is lost in 11c/11f in the low advection regions

Thank you for your suggestion. We have revised Fig. 11 to ensure clear presentation of information (Fig. R4).

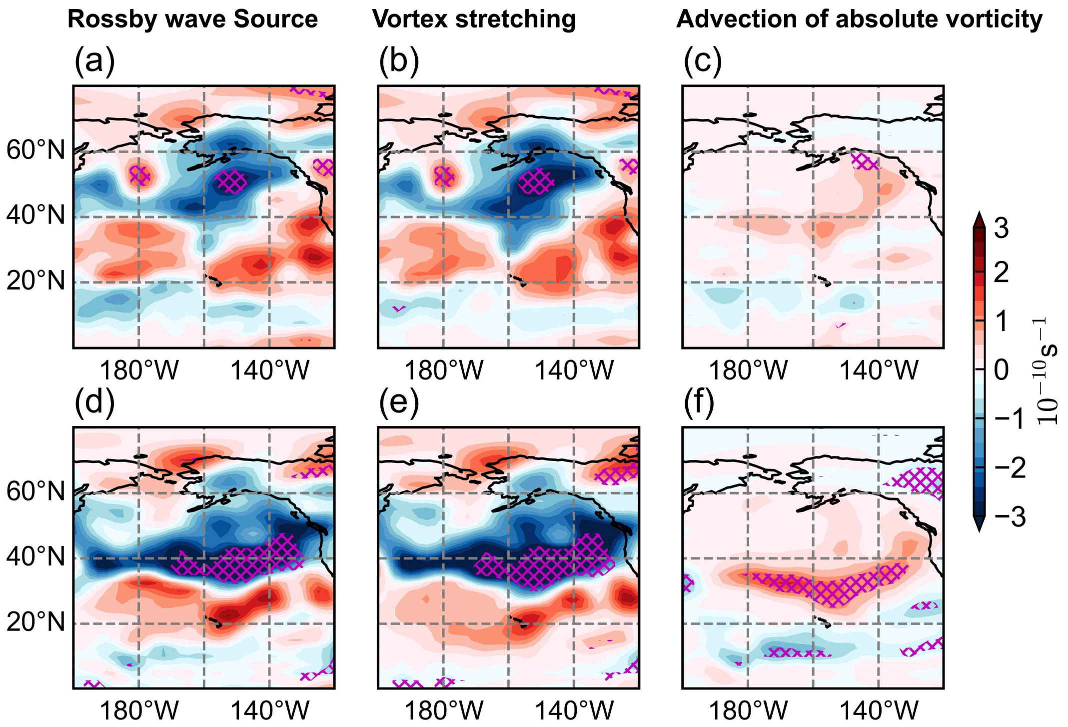

Figure R4. The same as Fig. 11 but replace the cyan stippling with magenta crossings.

Figure S11 – is a very strong plot demonstrating the modal deformation anomalies. What is the equivalent plot for EWSM?

The result can be found in Fig. R5a. For the EWSM, the sea ice deformation anomalies are almost entirely positive across the Arctic Ocean, a phenomenon that is interesting and worthy of discussion. Here, we propose a potential physical explanation. In the Canadian Arctic Archipelago and northern Greenland, increased sea ice deformation facilitates the significant outward advection of thick ice in the EWSM as mentioned in our manuscript. As this thick ice is transported toward the marginal seas of the Eastern Hemisphere, it melts and thins, with deformation intensifying simultaneously. This process also promotes the spreading of thick ice into a more uniform distribution, leading to increased sea ice concentration. In brief, intensified sea ice deformation in the thick ice regions of the Western Hemisphere within the central Arctic is one of the causes of EWSM formation, whereas intensified deformation in the Eastern Hemisphere is a consequence during the EWSM development process.

Furthermore, the impact of sea ice deformation on the EWSM and PASM differs in magnitude. The EWSM is more pronounced in winter than in summer as evident in Fig. 2b. Thus, even if intensified sea ice deformation leads to increased open water, the weak solar radiation in winter has a negligible effect on sea ice melting. In contrast, the PASM is significantly more influenced by sea ice deformation. As shown in Fig. 2c, positive phases of the PASM are concentrated in summer; intense sea ice deformation in the Pacific sector (Fig. R5b) would increase open water, enhancing oceanic absorption of solar radiation and thereby accelerating sea ice melting. Notably, the intense sea ice deformation in the Pacific sector during the PASM is closely linked to the dynamic effects of super cyclones (Fig. R3), which further corroborates our earlier discussion on the influence of super cyclones on the seasonal phase transition of the PASM.

Initially we did not present the result of Fig. R5a in the manuscript considering the above. We believe that sea ice deformation anomalies are not solely the cause of EWSM formation but also its consequence, which requires more detailed hemispheric-specific research. To minimize potential confusion for readers, we will include a brief discussion of this issue in the revised manuscript.

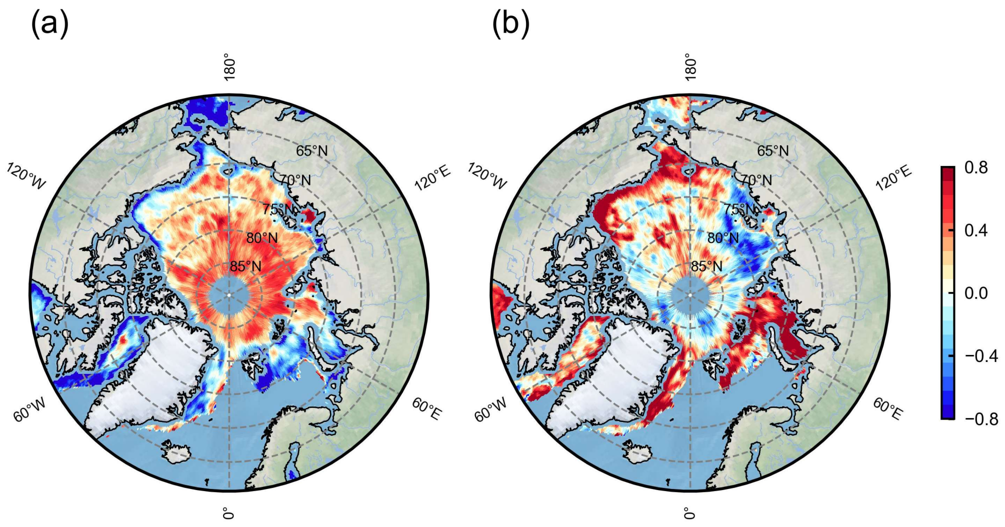

Figure R5. Composite differences between the positive and negative phases of the standardized anomalies of sea ice deformation for the (a) EWSM and (b) PASM.

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Conclusion

We greatly appreciate your insightful comments and valuable suggestions, which have provided important guidance for our subsequent revisions to the manuscript. We will carefully address all the concerns raised and further refine the work in line with the constructive feedback. We welcome any additional perspectives or advice as we proceed with the improvements.

Thank you for your time and efforts in reviewing our work.

Sincerely,

On behalf of all authors

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